

TURBULENT FLAME PROCESSES VIA DIFFUSION FLAME-VORTEX RING INTERACTIONS

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INTRODUCTION

Flame-vortex interactions are canonical configurations that can be used to study the underlying processes occurring in turbulent reacting flows. This configuration contains many of the fundamental aspects of the coupling between fluid dynamics and combustion that could be investigated with more controllable conditions than are possible under direct investigations of turbulent flames. Diffusion flame-vortex ring interaction contains many of the fundamental elements of flow, transport, combustion, and soot processes found in turbulent diffusion flames. Some of these elements include concentrated vorticity, entrainment and mixing, strain and nonequilibrium phenomena, diffusion and differential diffusion, partial premixing and diluent effects, soot formation and oxidation, and heat release effects. Such simplified flowfield allows the complex processes to be examined more closely and yet preserving the physical processes present in turbulent reacting flows. Furthermore, experimental results from the study of flame-vortex interactions are useful for the validation of numerical simulations and more importantly to deepen our understanding of the fundamental processes present in reacting flows.

Experimental and numerical results obtained under microgravity conditions of the diffusion flame-vortex ring interaction are summarized in this paper. Results are obtained using techniques that include Flame Luminosity Imaging (FLI), Laser Soot-Mie Scattering (LSMS), Computational Fluid Dynamics and Combustion (CFDC), and Diode Laser Spectroscopy/Iterative Temperature with Assumed Chemistry (DLS/ITAC).

RESULTS

Experiments were conducted under microgravity conditions at the NASA Glenn Research Center 2.2 seconds drop tower facility. Details of the experiment drop rig and its operations can be found in [1, 2]. A reacting vortex ring is generated by first establishing a diffusion flame at the exit of a 2-cm dia. nozzle. Fuel is then impulsively forced through the circular nozzle to generate a vortex ring which wraps the diffusion flame as it rolls up and propagates upstream. The configuration is analogous to the 2-D vortex pair analyses of Karagozian & Manda [3] and Manda & Karagozian [4]. Fuels include methane, ethane, propane, and nitrogen-diluted propane.

Flame luminosity from the burning vortex rings was imaged by a B/W CCD camera. Two cases of methane-air combustion are shown in Figs. 1 and 2. FLI was useful in the analysis of the flame

Figure 1. FLI results showing time evolution of methane-air combustion for $\Gamma = 482$ cm^2/s and $V=22$ cc. Frame rate is 30 Hz.

Figure 2. FLI results showing time evolution of methane-air combustion for $\Gamma = 212$ cm^2/s and $V=21$ cc. Frame rate is 30 Hz.

structure and ring dynamics of reacting vortex rings [1]. Ring trajectories have shown to have an increase in ring speed in the early stage of interaction, and a drastic decrease in ring speed in the latter stage. Fuel volume V and ring circulation Γ also played a role in the resulting flame structure and ring dynamics. Comparisons of propane and ethane cases have shown that radiative heat loss due to the presence of soot can also have an impact on the flame structure and ring dynamics [5]. Comparing Figs.1 and 2 shows that doubling the ring circulation while keeping fuel volume constant led to an increase in fuel consumption rate and flame height. Observations made from FLI were further examined using laser diagnostic tools and numerical simulations.

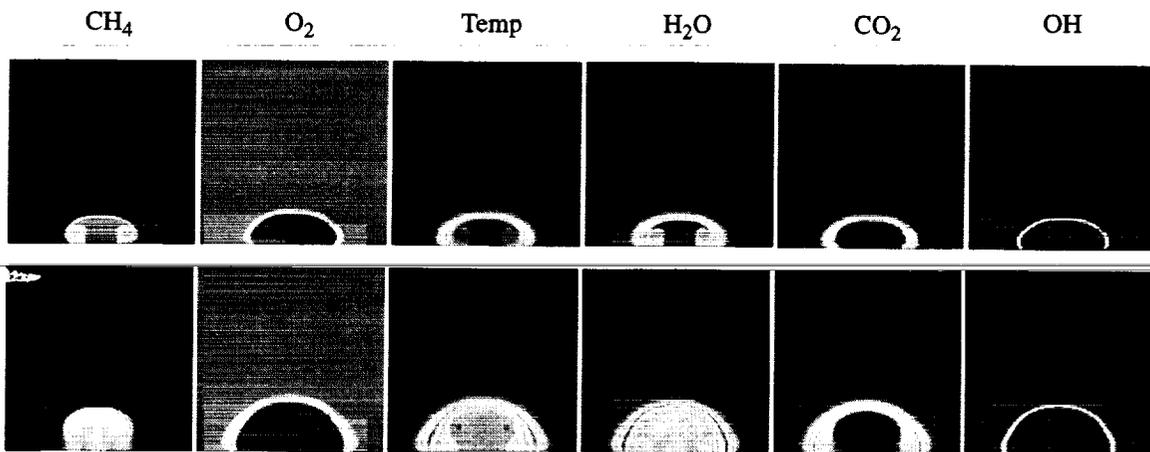


Figure 3. CFDC results showing mole fractions of chemical species and temperature for methane-air combustion with $\Gamma = 100$ cm^2/s and $V=10.5$ cc. Time between top and bottom frames is 0.2 sec. Color bars are as follow: 0-1 for CH_4 , 0-0.21 for O_2 , 300-2200 K for temperature, 0-0.19 for H_2O , 0-0.086 for CO_2 , and 0-0.0064 for OH.

The coupling between fluid dynamics and combustion was examined using numerical simulations by incorporating the conserved scalar approach in which the chemical species and temperature are functions of the conserved scalar (e.g. mixture fraction) and scalar dissipation rate [6, 7]. Chemistry assumptions included flame sheet modeling, equilibrium and non-equilibrium chemistry. Figure 3 is a methane-air reaction case showing results at two different times for temperature and mole fractions of CH_4 , O_2 , H_2O , CO_2 , and OH . Dilatation was found to be the dominant effect of combustion heat release in reacting vortex rings [5]. Note that no CO_2 was found inside the ring in regions where the fuel is still present. On the other hand H_2O is present throughout the interaction. Since no O_2 is found inside the vortex ring, modeling the fuel consumption as a diffusion-limited reaction seems appropriate [1].

The configuration of flame-vortex interaction allows the effects of fluid dynamics and chemistry on the soot processes to be studied. LSMS results can be used as tests for the numerical simulations of soot processes. Details of the experimental setup can be found in Chen *et al.* [8]. LSMS revealed new insights of the soot field inside reacting vortex rings which could not have been possible from inspection of FLI results. Soot was not present in regions of high strain and was found to be along the periphery of reacting vortex ring but inside the flame zone, as shown in Figs. 4 and 5. Future quantification of soot concentrations, such as Laser-Induced Incandescence technique, should be of great interest to the modeling of soot formation and oxidation.

DLS/ITAC was implemented to quantify CH_4 concentration in reacting vortex rings under microgravity conditions [9, 10]. The method of ITAC eliminates the need to directly measure temperature in order to quantify DLS measurements. The conserved scalar approach with the assumption of equilibrium chemistry or non-equilibrium chemistry allows the temperature to be determined via the mixture fraction and scalar dissipation rate. With the measurement of a single major species (e.g. CH_4) all the

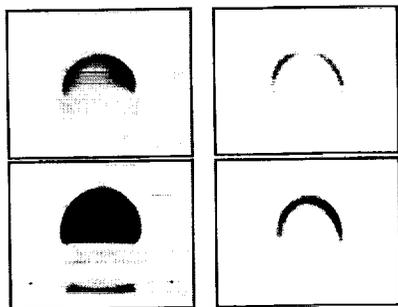


Figure 4. Propane-air combustion results from (left) FLI and (right) LSMS. Frame rate is 10 Hz. $V = 22$ cc and $\Gamma = 80$ cm^2/s .

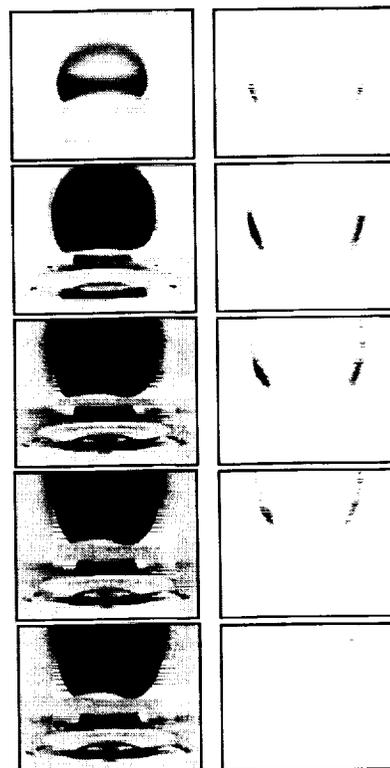


Figure 5. Propane-air combustion results from (left) FLI and (right) LSMS. Frame rate is 10 Hz. $V = 22$ cc and $\Gamma = 190$ cm^2/s .

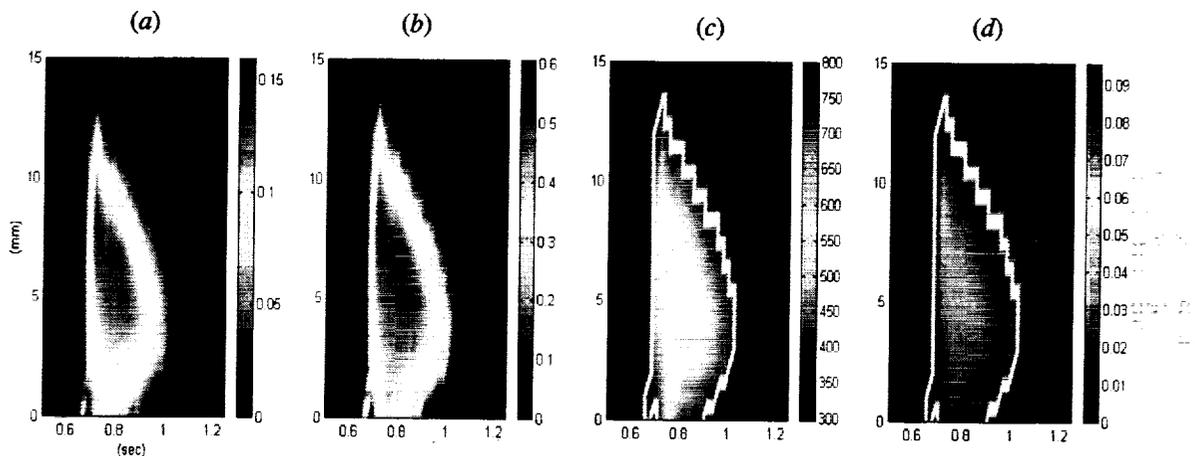


Figure 6. DLS/ITAC results for methane-air combustion at 0.2 inch above nozzle. $V = 21$ cc and $\Gamma = 212$ cm²/s. (a) Uncorrected CH₄ mole fraction from DLS [10], (b) corrected CH₄ mole fraction using ITAC, (c) temperature field in K, and (d) H₂O mole fraction as a function of drop time and radial distance from center of nozzle.

other major species (H₂O, CO₂, N₂) and temperature can be determined using ITAC via an iterative process. The method of ITAC extends diode laser spectroscopy measurement technique of a single species to a much broader measurement technique. Figure 6 shows the uncorrected and corrected CH₄ mole fraction along with the temperature field and H₂O mole fraction. The sawtooth edges in (c) and (d) are due to a lack of resolution. Future DLS/ITAC experiments will include measurements of H₂O or CO₂ which are useful in determining other major species in regions where CH₄ is not present. Measurements of OH will extend ITAC to flows where non-equilibrium chemistry effects are important.

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